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Evaluation of a Foreign Silicon Nitride as a Potential Gun Barrel Liner

by Jeffrey J. Swab, Dominic Danna, Charles Leveritt, and Stephanie Piraino

ARL-TR-5146 **April 2010**

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14. ABSTRACT A silicon nitride (Si_3N_4) ceramic manufactured by FCT Technologie GmbH, Rauenstein, Germany was subjected to a series of tests (mechanical, physical, thermal, and erosion) to determine if this material might have potential applications as gun barrel liners. The tests conducted were similar to earlier tests performed by the U.S. Army Research Laboratory (ARL) on a variety of ceramic materials, including silicon nitride, for the same application. The erosion behavior was comparable to the previously tested ceramics but the mechanical and thermal properties were inferior making it unlikely that it would survive the interior ballistic conditions of a gun barrel.			
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1. Summary

1.1 Purpose/Scope

In this study a silicon nitride ceramic manufactured by a German company was subjected to a series of tests (mechanical, physical, thermal, and erosion) to determine if this material might have potential applications as gun barrel liners. The tests conducted were similar to earlier tests performed by the U.S. Army Research Laboratory (ARL) on a variety of ceramic materials, including silicon nitride, for the same application.

1.2 Key Findings

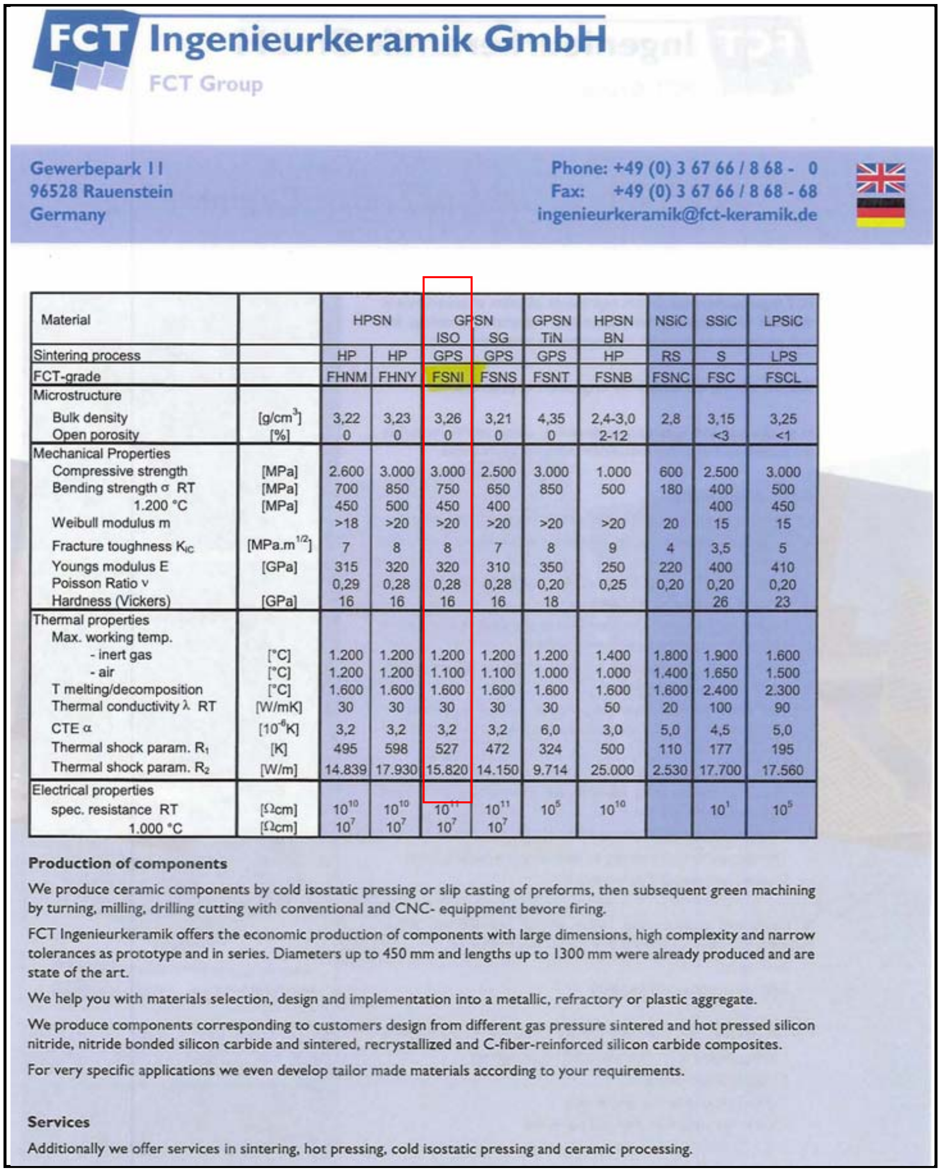
This silicon nitride performed quite well in the erosion testing. It exhibited a very low mass loss per test, which is in excellent agreement with other silicon nitrides previously subjected to the same erosion test procedure and parameters. However, when the mechanical and thermal properties of this Si_3N_4 are compared to the previously evaluated silicon nitrides and SiAlONs, it is inferior. The lower strength and toughness makes it unlikely that this Si_3N_4 would be able to handle the pressure and temperature profiles present during the interior ballistic event.

2. Introduction

The Army has a desire to develop lighter weight gun barrels with longer lifecycles that can handle the new high energy propellants currently available or under development. The steel barrels used in many systems have a short lifecycle and are susceptible to rapid and severe degradation when exposed to these new high-energy propellants. Ceramic materials have long been considered as a potential solution to these issues (*1–5*). It is anticipated that ceramic gun barrel liners will provide a 50% increase in barrel life with sustained accuracy for direct and indirect fire, enable a 20% increase in muzzle kinetic energy for direct fire, and provide a 5–25% weight reduction (per unit length of barrel) because of the combination of superior wear resistance, high temperature capability, and relatively low density that are inherent to ceramic materials. The development of a ceramic gun barrel will reduce maintenance costs while serving as an enabling technology for the use of higher energy propellants.

ARL completed a number of studies which have examined a variety of commercially-available ceramics for gun barrel applications (*6–14*). The ceramics examined included alumina (Al_2O_3), zirconia (ZrO_2), silicon carbide (SiC), silicon nitride (Si_3N_4) and silicon-aluminum oxynitride (SiAlON). These studies clearly identified the silicon nitride/SiAlON family of materials as the most promising for applications as gun barrel liners across a wide range of calibers.

In this study a Si_3N_4 ceramic manufactured by a company in Germany was subjected to tests similar to the ones used to evaluate the earlier silicon nitride ceramics (*6*) in order to determine if it also might be applicable for gun barrel applications. According to the manufacturer's property data sheet, figure 1, this Si_3N_4 has property values similar to the previously evaluated Si_3N_4 ceramics (*6*). The property values determined for this Si_3N_4 will be compared to the data already available on Si_3N_4.



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Material		HPSN		GPSN		GPSN	HPSN	NSiC	SSiC	LPSiC
				ISO	SG	TiN	BN			
Sintering process		HP	HP	GPS	GPS	GPS	HP	RS	S	LPS
FCT-grade		FHNM	FHNY	FSNI	FSNS	FSNT	FSNB	FSNC	FSC	FSCL
Microstructure										
Bulk density	[g/cm^3]	3,22	3,23	3,26	3,21	4,35	2,4-3,0	2,8	3,15	3,25
Open porosity	[%]	0	0	0	0	0	2-12		<3	<1
Mechanical Properties										
Compressive strength	[MPa]	2.600	3.000	3.000	2.500	3.000	1.000	600	2.500	3.000
Bending strength σ RT	[MPa]	700	850	750	650	850	500	180	400	500
1.200 °C	[MPa]	450	500	450	400				400	450
Weibull modulus m		>18	>20	>20	>20	>20	>20	20	15	15
Fracture toughness K_{IC}	[MPa.m$^{1/2}$]	7	8	8	7	8	9	4	3,5	5
Youngs modulus E	[GPa]	315	320	320	310	350	250	220	400	410
Poisson Ratio ν		0,29	0,28	0,28	0,28	0,20	0,25	0,20	0,20	0,20
Hardness (Vickers)	[GPa]	16	16	16	16	18			26	23
Thermal properties										
Max. working temp.										
- inert gas	[°C]	1.200	1.200	1.200	1.200	1.200	1.400	1.800	1.900	1.600
- air	[°C]	1.200	1.200	1.100	1.100	1.000	1.000	1.400	1.650	1.500
T melting/decomposition	[°C]	1.600	1.600	1.600	1.600	1.600	1.600	1.600	2.400	2.300
Thermal conductivity λ RT	[W/mK]	30	30	30	30	30	50	20	100	90
CTE α	[10^{-6}K]	3,2	3,2	3,2	3,2	6,0	3,0	5,0	4,5	5,0
Thermal shock param. R_1	[K]	495	598	527	472	324	500	110	177	195
Thermal shock param. R_2	[W/m]	14.839	17.930	15.820	14.150	9.714	25.000	2.530	17.700	17.560
Electrical properties										
spec. resistance RT	[Ωcm]	10^{10}	10^{10}	10^{11}	10^{11}	10^{5}	10^{10}		10^{1}	10^{5}
1.000 °C	[Ωcm]	10^{7}	10^{7}	10^{7}	10^{7}					

Production of components

We produce ceramic components by cold isostatic pressing or slip casting of preforms, then subsequent green machining by turning, milling, drilling cutting with conventional and CNC- equippment bevore firing.

FCT Ingenieurkeramik offers the economic production of components with large dimensions, high complexity and narrow tolerances as prototype and in series. Diameters up to 450 mm and lengths up to 1300 mm were already produced and are state of the art.

We help you with materials selection, design and implementation into a metallic, refractory or plastic aggregate.

We produce components corresponding to customers design from different gas pressure sintered and hot pressed silicon nitride, nitride bonded silicon carbide and sintered, recrystallized and C-fiber-reinforced silicon carbide composites.

For very specific applications we even develop tailor made materials according to your requirements.

Services

Additionally we offer services in sintering, hot pressing, cold isostatic pressing and ceramic processing.

Figure 1. Material data sheet provided by the manufacturer with the material. The Si_3N_4 evaluated in this effort is the gas pressure sintered (GPS) labeled FSNI highlighted by red box.

3. Material

The silicon nitride material to be evaluated was purchased from FCT Technologie GmbH, Rauenstein, Germany (FCT). It is fabricated using a GPS technique. Material was obtained from the manufacturer in three different geometries to facilitate the machining of the different test specimens required. Tubes 200-mm long with a nominal inner (Di) and outer (Do) diameters of 24 mm and 33 m, respectively, as well as two different cylinders: one 80-mm long with a 30-mm diameter and the other 150-mm long with a 20-mm diameter, were purchased.

4. Test Methodology

4.1 Mechanical Properties

Three different specimens were prepared and used to determine the strength of each ceramic. Uniaxial tension tests were used in an attempt to promote the volume-distributed flaws in the material while c-ring and o-ring tests highlighted the surface-distributed flaws on the outer and inner diameter respectively.

Cylindrical button-head tensile specimens were machined from the 150-mm long cylinders to the gage section dimensions listed in figure 9 of ASTM C1273 (*15*) with an overall specimen length of 135 mm. The room temperature uniaxial strength was determined using 10 specimens following the guidelines and equations in ASTM C1273 (*15*). The uniaxial tensile strength was calculated using equation 1:

$$S_u = \frac{P_{max}}{A}, \tag{1}$$

where S_u is the tensile strength, P_{max} is the breaking load, and A is the cross sectional area of the specimen.

C-ring specimens having a width of 8 mm with longitudinal 45° chamfers to a distance of 0.15 mm on the Do, and a slot height of 5.7 mm were machined from the tubular components and tested at room temperature in accordance with ASTM C1323 (*16*). A displacement rate of 0.5 mm/min was used to compressively and diametrally load the specimens to failure. A thin (0.005-in) graphite sheet was placed between the upper and lower contact locations to minimize the likelihood of contact-induced fracture. The geometry and failure loads were used to calculate the hoop or Do tangential failure stress ($\sigma_{\theta max}$) for each specimen according to the strength of materials solution in ASTM C1323:

$$\sigma_{\theta\max} = \frac{PR}{btr_o}\left[\frac{r_o - r_a}{r_a - R}\right], \tag{2}$$

where P is the failure load, R = $(r_o-r_i)/\ln(r_o/r_i)$, r_o is the outer c-ring radius, r_i is the inner c-ring radius, r_a is the average of r_o and r_i, b is width, and t is thickness or r_o-r_i.

The o-ring specimens were also machined from the tubular component to the same dimensions as the c-ring specimens but without a notch and with the chamfers on the Di of the specimen instead of the Do. These specimens were tested at room temperature and at 700 °C at a displacement rate of 0.5 mm/min. A 0.005-in thick graphite sheet was placed between the specimen and loading platens for testing at both temperatures. The specimens used in the high temperature testing were placed in the furnace and heated to temperature at a rate of 20 °C/min. Once at temperature each specimen was allowed to soak for 10 min to allow for thermal equilibrium to be achieved prior to the application of the load. The Di tangential failure stress ($\sigma_{\theta\max}$) at both temperatures was calculated using equation 3:

$$\sigma_{\theta\max} = \frac{P}{2}\left[0.637\frac{r_a(r_a - r_i)}{bt^3/12}\right]. \tag{3}$$

The variables have been defined previously for the c-ring specimens.

Each set of raw strength data was subsequently analyzed using a two-parameter Weibull regression according to ASTM C1239 (*17*). This analysis yielded a biased Wiebull modulus and characteristic strength.

Fracture toughness was determined using the procedures and equations in ASTM C1421 (*18*). Chevron notch specimens, nominally 3 mm×4 mm×50 mm in size with the D configuration notch (a_o = 1.40 ± 0.07 mm), were machined and then were fractured in three- or four-point bending. The fracture toughness (K_{Ivb}) was calculated using:

$$K_{Ivb} = Y^*_{\min}\left[\frac{P_{\max}(S_o - S_i)10^{-6}}{bw^{3/2}}\right], \tag{4}$$

where $Y^*_{\min}$ is the minimum stress intensity factor, P_{max} is the relevant maximum load that occurs during stable crack propagation, S_o and S_i are outer and inner support spans, respectively, b is the specimen width, and w the specimen height.

The Vickers hardness (H_v) was determined at room temperature using an indentation load of 300 g.

4.2 Thermal Properties

The thermal conductivity, heat capacity and coefficient of thermal expansion were determined between room temperature and 1000 ºC. ASTM E1461 (*19*) and ASTM C714 (*20*) were used to

obtain thermal diffusivity and heat capacity values using the laser flash method. A thermal conductivity was calculated from these values. The linear coefficient of thermal expansion was obtained using a prismatic specimen nominally 3 mm×4 mm×25 mm in size. Tests were conducted in a dual-rod dilatometer using a heating rate of 1 ºC/min following the procedure outlined in ASTM E228 (*21*). The data collection rate for this test was two datapoints/ºC.

4.3 Erosion Testing

The test used to simulate the interior ballistic conditions was a blow-out gun, figure 2. In this test the ceramic was exposed to interior ballistic conditions (temperature, pressure, etc.) created using JA-2 propellant (flame temperature–3420 K, impetus–1144 J/g). A ceramic nozzle was machined and placed in a steel surround, figure 3, creating a test piece that could be inserted into the gun. The nozzle was exposed to one shot then cleaned and weighed. The mass loss was determined and compared to the mass loss experienced by typical gun steel and the previously tested Si_3N_4 exposed to the same conditions. Each nozzle tested was exposed to a total of six shots.

Figure 2. Gun used for blow-out tests.

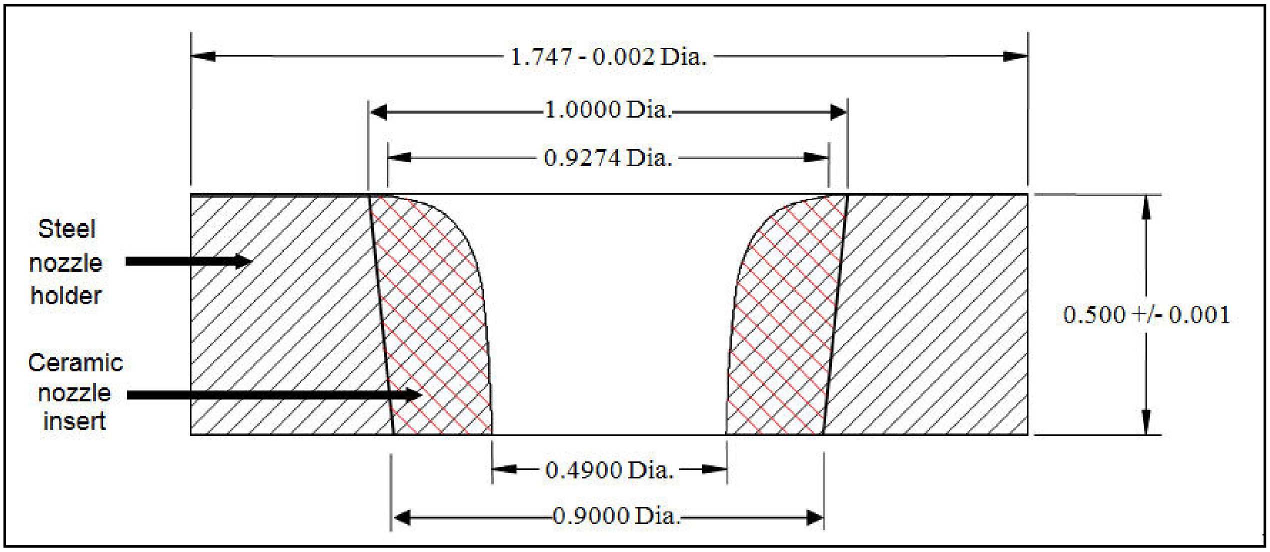


Figure 3. Nozzle assembly for the blow-out gun test. Dimensions are in inches.

5. Results

The results of the mechanical and thermal property testing are summarized in table 1 with the individual data points listed in the appendix. While the FCT material possesses a hardness value and thermal properties very similar to the Si_3N_4/SiAlON materials evaluated previously, it is inferior to these same materials when strength and fracture toughness are considered. Irrespective of the strength methodology employed there are two dominant flaw populations present in the material. One was a volume-distributed pore and the other was cracks or damage related to the surface finish. The pores, see figure 4, were essentially circular in shape with a diameter between 50 and 80 µm and were always located in the bulk of the specimen. The other flaw populations was always located at the specimen surface and due to either the machining process used to create the specimens for testing (for example, the chamfers machined on the c- or o-ring specimens) or the surface finish provided by the manufacturer. In the later instance the manufacturer was only provided the dimensional tolerances for the inner and outer diameter of tubes and not the procedure to achieve these dimensions or a requisite final surface finish. As a result, there were a number of specimens machined from these tubes that failed due to damage (cracks) imparted during the manufacturer's finishing process.

Table 1. Mechanical and thermal properties summary.

Density (g/cm^3)	3.27
Ave. Tensile Strength (MPa)	455 ± 146
Weibull Modulus	4.1
Ave. C-ring Strength (MPa)	582 ± 60
Weibull Modulus	12.8
Ave. O-ring Strength @ RT (MPa)	583 ± 50
Weibull Modulus	16.4
Ave. O-ring Strength @ 700°C (MPa)	466 ± 57
Weibull Modulus	8.7
K_{Ic} (MPa*√m) (Chevron Notch)	5.7 ± 0.1
Hardness (Hv) – 300g (GPa)	13.3 ± 0.3
Thermal Conductivity (W/m-K) 25°C - 1000°C	25.2 - 14.2
Heat Capacity (J/g-K) 25°C - 1000°C	0.7 - 1.3
Ave. Coefficient of Thermal Expansion (25°C - 1000°C)	2.1 - 3.6

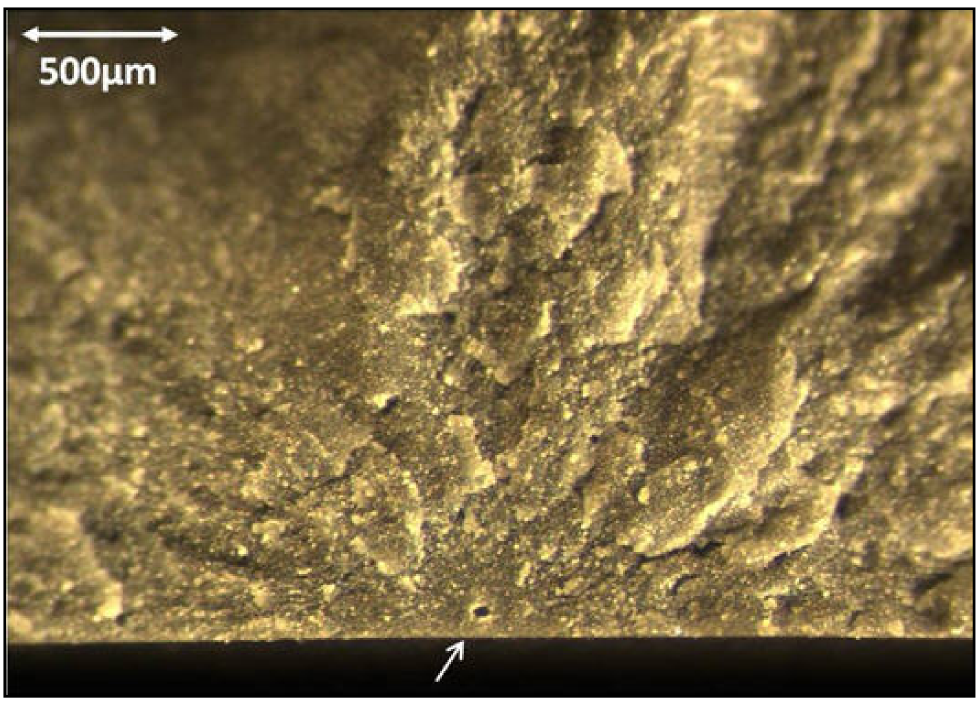


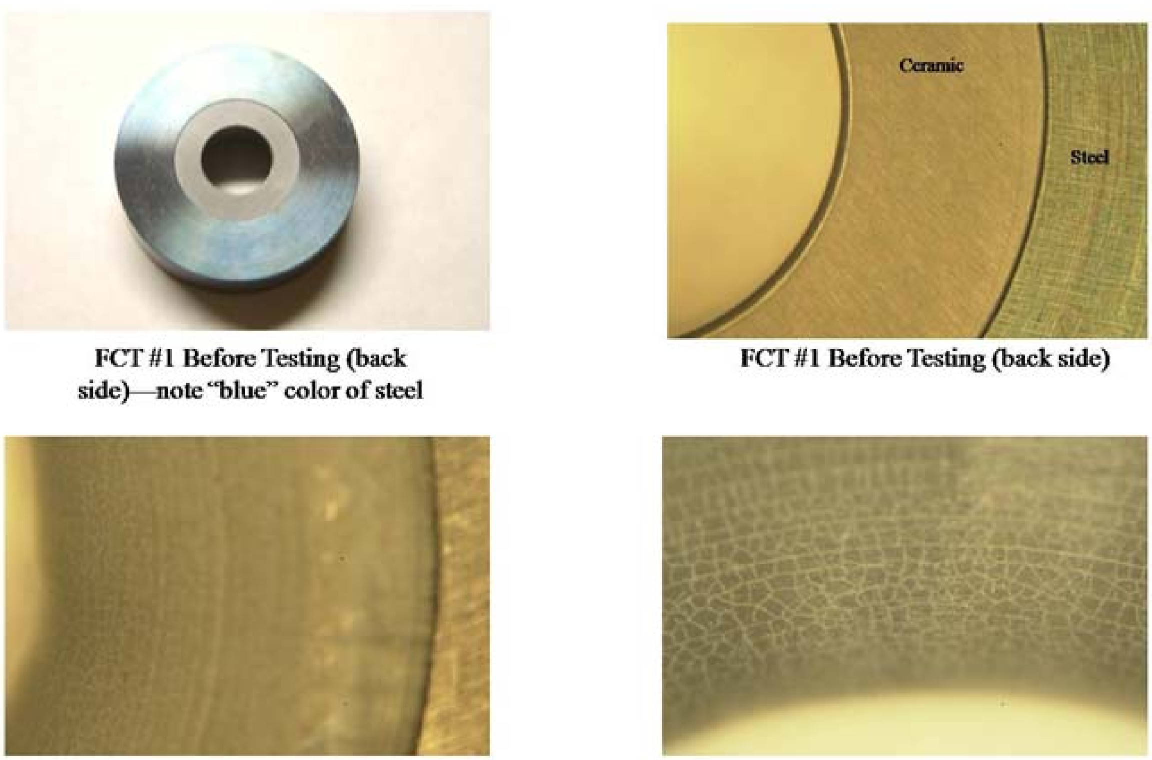
Figure 4. Example of a pore as the strength-limiting flaw. White arrow shows that the pore is located just beneath the tensile surface of this c-ring specimen. Specimen strength was 565 MPa.

The results from the erosion testing are summarized in table 2. The data shows that the Si_3N_4 nozzle experiences a small and consistent mass loss with each shot. Additionally, there was no

change in the diameter of the nozzle throat with each test shot but there was evidence of heat checking and discoloration of the front and back sides of both nozzles, see figures 5 and 6. The physical and structural integrity of both nozzles was maintained throughout the testing. These findings are in agreement with previous erosion testing results on other Si_3N_4/SiAlON materials (*7*).

Table 2. Summary of the mass loss/shot for FCT Si_3N_4.

Shot #	Nozzle #1 Mass Loss (mg)	Nozzle #2 Mass Loss (mg)
1	0.2	+2.1
2	2.6	2.8
3	3.4	2.2
4	2.8	3.0
5	3.3	4.5
6	4.3	3.4
Average	**2.8**	**2.3**



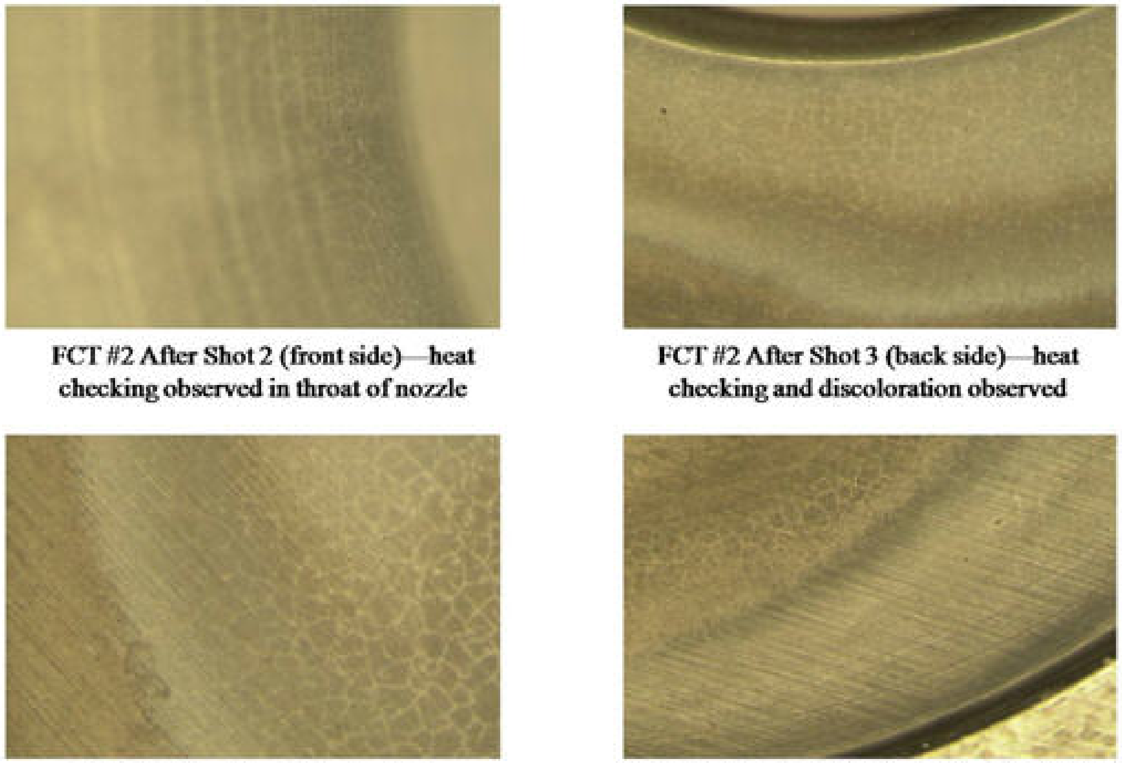
FCT #1 Before Testing (back side)—note "blue" color of steel

FCT #1 Before Testing (back side)

FCT #1 After Shot 3 (front side)—heat checking is observed in throat area

FCT #1 After Shot 6 (back side)—heat checking more prevalent; follows machining pattern

Figure 5. Images of FCT nozzle #1 before and after erosion testing.



FCT #2 After Shot 2 (front side)—heat checking observed in throat of nozzle

FCT #2 After Shot 3 (back side)—heat checking and discoloration observed

FCT #2 After Shot 5 (back side)

FCT #2 After Shot 6 (back side)—heat checking observed concurrently with discoloration as a result of combustion gases

Figure 6. Images of FCT nozzle #2 after erosion testing.

6. Conclusions

This Si_3N_4 performed quite well in the erosion testing. It exhibited a very low mass loss per test, which is in excellent agreement with other silicon nitrides previously subjected to the same erosion test procedure and parameters. However, when the mechanical and thermal properties of this Si_3N_4 are compared to the previously evaluated silicon nitrides and SiAlONs it is inferior. The lower strength and toughness makes it unlikely that this Si_3N_4 would be able to handle the pressure and temperature profiles present during an interior ballistic event.

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Appendix. Mechanical Property Data

Table A-1. Room temperature tensile strength data.

Specimen #	Length (mm)	Diameter (mm)	Radius (mm)	Area (mm^2)	Fracture Load (N)	σ_{MAX} (MPa)
FCT-1	150	6.283	3.142	31.00	7505.0	242.1
FCT-2	150	6.309	3.155	31.26	8575.0	274.3
FCT-3	150	6.314	3.157	31.31	15196.4	485.3
FCT-4	150	6.286	3.143	31.03	15064.3	485.4
FCT-5	150	6.286	3.143	31.03	17093.0	550.8
FCT-6	150	6.302	3.151	31.19	17940.2	575.1
FCT-7	150	6.309	3.155	31.26	18655.4	596.8
FCT-8	150	6.318	3.159	31.35	18605.6	593.5
FCT-9	150	6.355	3.178	31.72	9228.2	290.9
					Average:	**454.9**
					STD:	**145.6**

Table A-2. Room temperature c-ring strength data.

Specimen #	Do (mm)	Di (mm)	Slot (mm)	Thickness, b (mm)	Width, t (mm)	Load (N)	σ_{MAX} (MPa)
FCT-7-1	33.05	24.02	6.14	7.99	4.515	1263.51	564.7
FCT-7-2	33.04	24.04	6.14	7.98	4.500	1209.90	545.5
FCT-7-3	33.06	24.05	6.13	7.98	4.505	1351.79	608.3
FCT-7-4	33.05	24.04	6.15	7.97	4.505	1344.22	605.4
FCT-7-5	33.04	24.03	6.14	7.94	4.505	1288.23	582.2
FCT-7-6	33.04	24.05	6.13	7.98	4.495	1292.48	584.2
FCT-9-1	33.02	23.96	6.14	7.97	4.530	1178.98	523.5
FCT-9-2	33.06	23.96	6.11	7.97	4.550	1221.33	537.6
FCT-9-3	33.02	23.97	6.14	7.96	4.525	1156.77	515.6
FCT-9-4	33.02	23.96	6.14	7.97	4.530	946.39	420.2
FCT-9-5	33.02	23.95	6.11	7.96	4.535	1366.11	605.8
FCT-9-6	33.01	23.99	6.11	7.97	4.510	1424.10	638.7
FCT-9-7	33.01	23.97	6.12	7.96	4.520	1514.63	676.6
FCT-10-1	33.04	24.06	6.15	7.97	4.490	1394.57	632.8
FCT-10-2	33.04	24.02	6.13	7.97	4.510	1349.68	606.1
FCT-10-3	33.04	24.02	6.15	7.98	4.510	1428.29	640.6
FCT-10-4	33.03	24.04	6.13	7.98	4.495	1250.94	565.2
FCT-10-5	33.04	24.02	6.15	7.98	4.510	1391.73	624.2
						Average:	**582.1**
						STD:	**59.5**

Table A-3. Room temperature o-ring strength data.

Specimen #	Do (mm)	Di (mm)	B (mm)	Fracture Load (N)	σ_{MAX} (MPa)
FCT-3-1	33.10	24.04	7.96	3407.6	569.5
FCT-3-2	33.01	24.05	7.97	3577.2	609.6
FCT-3-3	33.01	24.03	7.96	3700.1	628.3
FCT-3-4	33.01	24.05	7.97	3625.6	617.9
FCT-3-5	33.01	24.05	7.97	3454.3	588.7
FCT-7-7	33.04	24.04	7.96	3213.8	543.7
FCT-7-8	33.05	24.04	7.97	2979.7	502.4
FCT-7-9	33.05	24.03	7.97	3023.9	508.7
FCT-7-10	33.04	24.04	7.96	3720.2	629.4
FCT-7-11	33.01	24.03	7.96	3727.1	632.9
				Average:	**583.1**
				STD:	**49.9**

Table A-4. O-ring strength data at 700 °C.

Specimen #	Do (mm)	Di (mm)	B (mm)	Fracture Load (N)	σ_{MAX} (MPa)
FCT-3-8	33.01	24.05	7.970	2900.8	494.3
FCT-3-9	33.01	24.05	7.950	2652.1	453.1
FCT-3-10	33.01	24.04	7.970	3081.3	523.9
FCT-3-11	33.01	24.05	7.960	2786.4	475.4
FCT-3-12	33.01	24.05	7.960	2452.0	418.4
FCT-7-12	33.05	24.04	7.950	2656.9	449.1
FCT-7-13	33.04	24.05	7.970	2568.4	435.0
FCT-7-14	33.05	24.04	7.970	2752.3	464.1
FCT-7-15	33.05	24.06	7.970	3418.8	579.3
FCT-7-16	33.05	24.04	7.950	2232.6	377.4
FCT-7-17	33.04	24.04	7.940	3222.5	546.6
FCT-10-6	33.03	23.97	7.970	2574.6	428.7
FCT-10-7	33.03	23.99	7.970	2499.2	418.1
				Average:	**466.42**
				STD:	**56.84**

Table A-5. Chevron notch fracture toughness data.

Specimen #	**B (mm)**	**W (mm)**	**a_0 (mm)**	**a_1 (mm)**	**a_{11} (mm)**	**a_{12} (mm)**	**Fracture Load (N)**	**K_{IC} (MPa*m$^{1/2}$)**
1	2.986	3.997	1.433	3.748	3.716	3.780	18.3	5.84
2	3.001	4.001	1.344	3.711	3.710	3.712	18.9	5.64
3	2.995	3.997	1.372	3.720	3.733	3.707	19.1	5.81
4	2.982	3.997	1.343	3.617	3.558	3.675	19.0	5.55
5	2.976	4.004	1.370	3.675	3.659	3.690	19.3	5.71
6	2.991	4.015	1.410	3.746	3.756	3.736	18.8	5.80
							Average:	**5.73**
							STD:	**0.11**

Table A-6. Vickers hardness data at 300 g indention load.

Indent #	**Ave d (um)**	**Ave d (mm)**	**HV (GPa)**
1	20.3	0.0203	13.2
2	20.6	0.0206	12.9
3	20.3	0.0203	13.2
4	20.1	0.0201	13.5
5	20.0	0.0200	13.6
Average:	**20.3**	**0.0203**	**13.3**
STD:	**0.2**	**0.0002**	**0.3**

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